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EXAMINER

SHIFERAW, ELEN I A

ART UNIT PAPER NUMBER

2136

DATE MAILED: 06/07/2005

Please find below and/or attached an Office communication concerning this application or proceeding.

**Advisory Action  
Before the Filing of an Appeal Brief**

Application No.

09/896,197

Applicant(s)

ROELSE, PETRUS LAMBERTUS  
ADRIAANUS

Examiner

Eleni A. Shiferaw

Art Unit

2136

--The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

THE REPLY FILED 5/21/2005 FAILS TO PLACE THIS APPLICATION IN CONDITION FOR ALLOWANCE.

1. ☒ The reply was filed after a final rejection, but prior to or on the same day as filing a Notice of Appeal. To avoid abandonment of this application, applicant must timely file one of the following replies: (1) an amendment, affidavit, or other evidence, which places the application in condition for allowance; (2) a Notice of Appeal (with appeal fee) in compliance with 37 CFR 41.31; or (3) a Request for Continued Examination (RCE) in compliance with 37 CFR 1.114. The reply must be filed within one of the following time periods:

- a) ☐ The period for reply expires \_\_\_\_\_ months from the mailing date of the final rejection.  
b) ☒ The period for reply expires on: (1) the mailing date of this Advisory Action, or (2) the date set forth in the final rejection, whichever is later. In no event, however, will the statutory period for reply expire later than SIX MONTHS from the mailing date of the final rejection.

Examiner Note: If box 1 is checked, check either box (a) or (b). ONLY CHECK BOX (b) WHEN THE FIRST REPLY WAS FILED WITHIN TWO MONTHS OF THE FINAL REJECTION. See MPEP 706.07(f).

Extensions of time may be obtained under 37 CFR 1.136(a). The date on which the petition under 37 CFR 1.136(a) and the appropriate extension fee have been filed is the date for purposes of determining the period of extension and the corresponding amount of the fee. The appropriate extension fee under 37 CFR 1.17(a) is calculated from: (1) the expiration date of the shortened statutory period for reply originally set in the final Office action; or (2) as set forth in (b) above, if checked. Any reply received by the Office later than three months after the mailing date of the final rejection, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

**NOTICE OF APPEAL**

2. ☐ The Notice of Appeal was filed on \_\_\_\_\_. A brief in compliance with 37 CFR 41.37 must be filed within two months of the date of filing the Notice of Appeal (37 CFR 41.37(a)), or any extension thereof (37 CFR 41.37(e)), to avoid dismissal of the appeal. Since a Notice of Appeal has been filed, any reply must be filed within the time period set forth in 37 CFR 41.37(a).

**AMENDMENTS**

3. ☐ The proposed amendment(s) filed after a final rejection, but prior to the date of filing a brief, will not be entered because  
(a) ☐ They raise new issues that would require further consideration and/or search (see NOTE below);  
(b) ☐ They raise the issue of new matter (see NOTE below);  
(c) ☐ They are not deemed to place the application in better form for appeal by materially reducing or simplifying the issues for appeal; and/or  
(d) ☐ They present additional claims without canceling a corresponding number of finally rejected claims.

NOTE: \_\_\_\_\_. (See 37 CFR 1.116 and 41.33(a)).

4. ☐ The amendments are not in compliance with 37 CFR 1.121. See attached Notice of Non-Compliant Amendment (PTOL-324).

5. ☐ Applicant's reply has overcome the following rejection(s): \_\_\_\_\_.

6. ☐ Newly proposed or amended claim(s) \_\_\_\_\_ would be allowable if submitted in a separate, timely filed amendment canceling the non-allowable claim(s).

7. ☒ For purposes of appeal, the proposed amendment(s): a) ☐ will not be entered, or b) ☒ will be entered and an explanation of how the new or amended claims would be rejected is provided below or appended.

The status of the claim(s) is (or will be) as follows:

Claim(s) allowed: \_\_\_\_\_.

Claim(s) objected to: \_\_\_\_\_.

Claim(s) rejected: 1-20

Claim(s) withdrawn from consideration: \_\_\_\_\_.

**AFFIDAVIT OR OTHER EVIDENCE**

8. ☐ The affidavit or other evidence filed after a final action, but before or on the date of filing a Notice of Appeal will not be entered because applicant failed to provide a showing of good and sufficient reasons why the affidavit or other evidence is necessary and was not earlier presented. See 37 CFR 1.116(e).

9. ☐ The affidavit or other evidence filed after the date of filing a Notice of Appeal, but prior to the date of filing a brief, will not be entered because the affidavit or other evidence failed to overcome all rejections under appeal and/or appellant fails to provide a showing of a good and sufficient reasons why it is necessary and was not earlier presented. See 37 CFR 41.33(d)(1).

10. ☐ The affidavit or other evidence is entered. An explanation of the status of the claims after entry is below or attached.

**REQUEST FOR RECONSIDERATION/OTHER**

11. ☒ The request for reconsideration has been considered but does NOT place the application in condition for allowance because:  
See Continuation Sheet \_\_\_\_\_.

12. ☐ Note the attached Information Disclosure Statement(s). (PTO/SB/08 or PTO-1449) Paper No(s). \_\_\_\_\_

13. ☒ Other: See attachment

See Continuation Sheet (PTOL-303 (Rev. 4-05))

Regarding claim 2, Heys teaches an efficient implementation of a secure block cipher if the S-boxes are carefully/appropriately selected and the cipher is strengthened by replacing the permutation of bits between S-box rounds (see page 1 col. 1 lines 1-16, and col. 2 lines 15-27). Regarding claim 13, Heys teaches randomly selecting a permutation from a stored set of permutation each time before using the S-boxes to convert an input data block into an output data block (see page 1 col. 2 lines 15-27 and page 2 col. 1 lines 5-16). Regarding claim 14, Heys teaches selecting S-boxes depending upon the received signal information and replacing the permutation between rounds of S-boxes to improve the security (see page 4 col. 1 lines 4-31).

  
AYAZ SHEIKH  
SUPERVISORY PATENT EXAMINER  
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On The Design Of Secure Block Ciphers

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On The Design Of Secure Block Ciphers

Heys, H. M. ; Tavares, S. E.

# On the Design of Secure Block Ciphers

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**Abstract** — In this paper, we examine a class of block ciphers referred to as substitution-permutation networks or SPNs. We assert that the basic SPN architecture can be used to provide an efficient implementation of a secure block cipher if the system S-boxes are carefully selected and connected with an appropriate linear transformation. Specifically, it is shown that  $8 \times 8$  S-boxes which possess good diffusion and nonlinearity properties may be effectively used as components of a secure block cipher. As well, it is demonstrated that the cipher may be strengthened by replacing the permutation of bits between S-box rounds with a diffusive linear transformation.

## I. Introduction

Since its introduction in 1977, the Data Encryption Standard (DES) [1] has become the most widely applied private key block cipher. Recently, a hardware design to effectively break DES using exhaustive search was outlined by Wiener [2]. Unfortunately, since the DES design principles have never been fully disclosed, it is not generally known how to efficiently modify the DES algorithm to allow for different block or key sizes. This suggests that there is a need to replace DES with a secure, flexible block cipher whose design is well understood. In this paper, we contribute to the achievement of this objective by examining a

simple, yet elegant class of block ciphers referred to as substitution-permutation networks or SPNs.

Feistel [3][4] was the first to suggest that an SPN architecture consisting of rounds of nonlinear substitutions (S-boxes) connected by bit position permutations was a simple, effective implementation of Shannon's concept of a "mixing transformation" based on the principles of "confusion" and "diffusion" [5]. Many modern block ciphers, including DES, FEAL [6], and LOKI [7], while deviating from Feistel's basic SPN model, are based on Shannon's fundamental concepts.

In this paper, we show that appropriately selected S-boxes and S-box interconnection transformations can be used to increase a cipher's resistance to differential [8] and linear cryptanalysis [9] and are also effective in improving a cipher's adherence to the important cryptographic property referred to as the strict avalanche criterion (SAC) [10]. In particular, we examine the use of large  $8 \times 8$  S-boxes that are selected to provide strong diffusion and nonlinearity characteristics and we analyze the effectiveness of a novel application of linear transformations between rounds of S-boxes.

## II. Background

We shall consider a general  $N$ -bit SPN as consisting of  $R$  rounds of  $n \times n$  S-boxes. The plaintext and ciphertext are  $N$ -bit vectors denoted as

$P = [P_1 P_2 \dots P_N]$  and  $C = [C_1 C_2 \dots C_N]$ , respectively. An S-box in the network is defined as an  $n$ -bit bijective mapping  $S$ . A simple example of an SPN is illustrated in Figure 1.

In general, S-boxes may be keyed by (1) using key bits to select which mappings are used for the S-boxes or (2) XORing key bits with network bits prior to entering the S-boxes. We shall assume in our discussion that the network is keyed by XORing  $N$  bits of key (as determined by the key scheduling algorithm) before each round and after the last round of substitutions. Decryption is performed by running the data backwards through the network (i.e., applying the key scheduling algorithm in reverse and using the inverse S-boxes).

Rather than strictly confining ourselves to the basic form of S-boxes connected by a bit position permutation, in this paper we consider the more general model of S-boxes connected by invertible linear transformations. However, for consistency, we still refer to the more general architecture as an SPN.

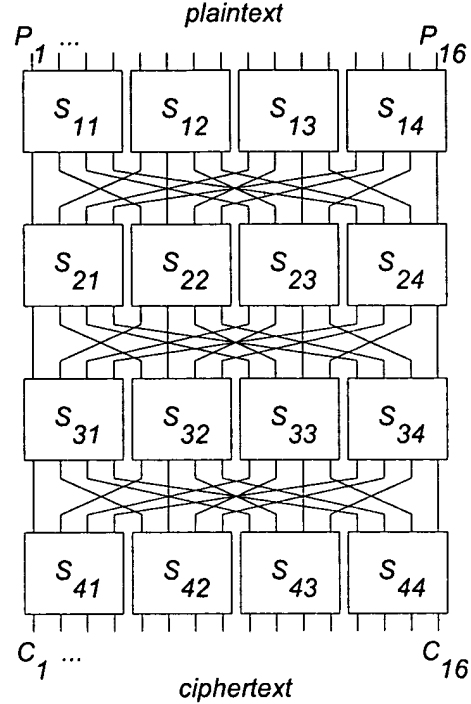
### III. Important Cryptographic Properties

In general, we consider that cryptographic properties may be categorized as either static or dynamic. Static properties encompass the relationships among plaintext, ciphertext, and key bits when the plaintext or key bits are not changing; dynamic properties refer to the relationships of plaintext, ciphertext, and key bit changes when a subset of plaintext or key bits are changed.

Important static properties include:

(S1) *completeness* [11]

- each ciphertext bit is a function of all plaintext and key bits



**Figure 1.** SPN with  $N = 16$ ,  $R = 4$ , and  $n = 4$

(S2) *nonlinearity* [12]

- each ciphertext bit has low correlation to a linear system equation

(S3) *static information theoretic properties* [13]

- partial knowledge of plaintext/key bits does not reveal any information about the ciphertext

Important dynamic properties include:

(D1) *strict avalanche criterion (SAC)* [10]

- a one bit plaintext/key change causes each ciphertext bit to change with a probability of  $1/2$

(D2) *low probability differential characteristics* [8]

- occurrence of a particular sequence of XOR differential pairs corresponding to each round is unlikely

(D3) *dynamic information theoretic properties* [13]

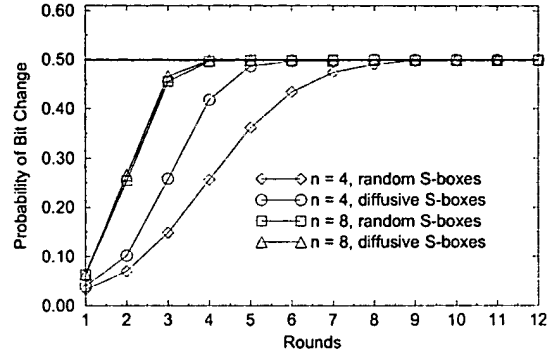
- partial knowledge of plaintext/key bit changes does not reveal any information about the ciphertext bit changes

The strict avalanche criterion and information theoretic properties — properties S3, D1, and D3 — can be considered as measures of a cipher’s randomness and, hence, its resistance to certain kinds of statistical attacks. For example, it can be shown that systems which do not satisfy SAC for key bit changes may be susceptible to key clustering attacks [14]. The remaining properties — S1, S2, D2 — are required to ensure immunity to clustering attacks [15], linear cryptanalysis [9], and differential cryptanalysis [8]. In this paper, we focus our attention on the properties of SAC, nonlinearity, and differential characteristics.

#### IV. S-box Design

In this section we discuss how S-boxes may be selected to provide the cryptographic properties of interest.

An important S-box property which is useful in improving resistance to differential cryptanalysis (by decreasing differential characteristic probabilities) is the rapid diffusion of bit changes [16][17][12]. (A simple example of S-box diffusion is the property that a one bit input change results in two or more output changes. We refer to this as first order diffusion and it is interesting to note that the DES S-boxes satisfy this property. Higher order diffusion is also possible [12].) As well, several authors [18][19][20] have suggested that selecting S-boxes with low probability XOR differential pairs is useful in ensuring low probability characteristics. In [17], O’Connor illustrates that for large  $n$ , the maximum XOR pair probability,  $p_\delta$ , is expected to be small,  $p_\delta \leq n/2^{n-1}$ .



**Figure 2.** Experimental SAC for Different S-box Types

We propose selecting S-boxes to satisfy both diffusion and small XOR pair probabilities. In consideration of O’Connor’s result, we have found that this is most easily done for large S-boxes. (Our experiments have involved S-boxes for which  $n \leq 8$ .) We have discovered that  $8 \times 8$  S-boxes satisfying good diffusion characteristics may be efficiently selected using a depth-first-search algorithm. Among the S-boxes generated with good diffusion, it was easy to find S-boxes which were highly nonlinear ( $NL \geq 96$ ) and satisfied  $p_\delta \leq 2^{-4}$ . Consider the following example.

**Example 1:** For an 8-round SPN, using  $8 \times 8$  S-boxes which satisfy first order diffusion with  $NL \geq 96$  and  $p_\delta \leq 2^{-4}$ , using reasonable assumptions about the permutations, it can be shown [12] that the minimum number of chosen plaintexts required for differential cryptanalysis is  $N_D \approx 2^{40}$  and the number of known plaintexts required for linear cryptanalysis is  $N_L \approx 2^{34}$ . For a 64-bit block cipher using a 40-bit key, this SPN provides a reasonable level of security when compared to the  $2^{40}$  key trials required in an exhaustive key search.

We consider that an SPN is stronger in relation to a criterion when fewer rounds are required to reasonably achieve the criterion. Using this definition of cryptographic strength, we have discovered that

- (1) large S-boxes strengthen an SPN’s SAC properties and

- (2) strong diffusion characteristics strengthen an SPN's SAC properties (particularly for small S-boxes)

These conclusions are supported analytically in [21] and experimentally by the results presented in Figure 2. The curves of Figure 2 illustrate the probability of a ciphertext bit change as a function of the number of rounds in the network. The curves represent experimental data obtained for 64-bit SPNs using optimal permutations [21] and different sized S-boxes randomly selected to satisfy first order diffusion. The results presented are based on  $10^4$  randomly selected plaintexts and, if SAC was perfectly satisfied, we would expect the probability to be  $1/2$ .

## V. S-box Interconnection

In this section, we consider improving the security of an SPN by replacing the permutation between rounds of S-boxes with a suitable invertible linear transformation. Consider, for example, a linear transformation such as

$$\mathbf{V} = \pi(\mathcal{L}(\mathbf{U})) \quad (1)$$

where  $\mathbf{V} = [V_1 \ V_2 \ \dots \ V_N]$  is the vector of input bits to a round of S-boxes,  $\mathbf{U} = [U_1 \ U_2 \ \dots \ U_N]$  is the vector of bits from the previous round output,  $\mathcal{L}(\mathbf{U}) = [L_1(\mathbf{U}) \ \dots \ L_N(\mathbf{U})]$  is a diffusive invertible linear transformation, and  $\pi$  is a permutation such that no two outputs of an S-box are connected to one S-box in the next round. The transformation  $L_i(\mathbf{U})$  is given by

$$L_i(\mathbf{U}) = U_i \oplus Q \quad (2)$$

where  $Q = U_1 \oplus U_2 \oplus \dots \oplus U_N$ .

Using such a transformation between rounds of S-boxes is useful in promoting rapid diffusion of bit changes. Let  $\eta_U$  represent the number of bit changes in vector  $\mathbf{U}$  and  $\eta_V$  represent the

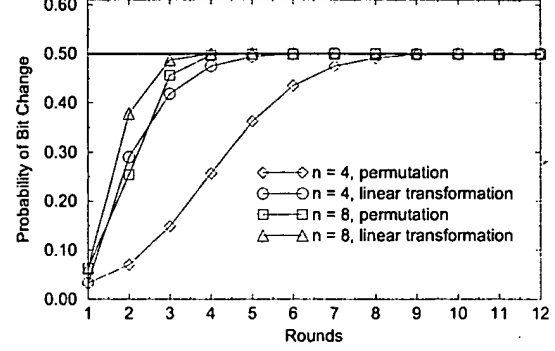


Figure 3. Experimental SAC for Linear Transformation

number of bit changes in vector  $\mathbf{V}$ . It can be shown [21] that

$$\eta_V = \begin{cases} \eta_U & , \eta_U \text{ even} \\ N - \eta_U & , \eta_U \text{ odd} \end{cases} \quad (3)$$

Hence, a differential with a small, odd number of bit changes is translated into a differential with a large number of bit changes, whereas differentials with even changes remain unaffected. For example, if  $N = 64$ , a one bit change from the output of round  $r$  is translated into a 63 bit change to the input of round  $r + 1$ .

It can be shown [12] that the diffusion of bit changes by the linear transformation is useful in decreasing the upper bound on the differential characteristic probability when S-boxes are used which have no diffusion. As well, it may be demonstrated [12] that using such a linear transformation, the effectiveness of a linear approximation to the overall cipher can be decreased by requiring a larger number of S-box linear approximations to be included in the system linear expression.

**Example 2:** For an 8-round SPN, using  $8 \times 8$  S-boxes which satisfy second order diffusion with  $N_L \geq 96$  and  $p_\delta \leq 2^{-4}$  and using the linear transformation of (1), it can be shown [12] that  $N_D \approx 2^{52}$  and  $N_L \approx 2^{50}$ . Note that, for a 64-bit SPN using a 64-bit key, the level of security is comparable to DES (with a 56-bit key) which has  $N_D \approx 2^{47}$  and  $N_L \approx 2^{47}$  and is reasonable when compared to the  $2^{64}$  key trials required by exhaustive key search.



The diffusive effect of the linear transformation of (1) is also useful in strengthening the SAC properties of the SPN. Figure 3 illustrates the probability of a ciphertext bit change as a function of the number of network rounds based on  $10^4$  experimental plaintexts for a 64-bit SPN with different sized S-boxes.

## VI. Key Scheduling

The keying mechanism is an important aspect of block cipher security. We recommend the application of a rotating key, that the sub-key applied at each round is unique, and that all key bits are applied as early as possible in the network.

It is interesting to note that the SPN structure considered in this paper is immune to the related-keys attack presented in [22]. In DES-like ciphers the related-keys attack exploits the half block of ciphertext that comes directly from the output of the previous round. In a basic SPN, it is not possible to examine the input to any round, thereby preventing any exploitation of the relationship between the sub-keys of consecutive rounds.

A block cipher is said to have a "weak" key if encryption using the key is equivalent to decryption using the same key. That is, double encryption of the plaintext results in the original plaintext. Since decryption does not use the same substitutions (the inverse S-boxes are used), the basic SPN structure has the advantage that there are no obvious weak keys. The keying structure itself has no apparent tendency to allow weak keys.

## VII. Conclusions

In this paper, we have suggested that the basic SPN structure, motivated by Shannon and introduced by Feistel, is an elegant structure for the design of secure block ciphers. The ease

of randomly selecting large S-boxes that satisfy good diffusion and nonlinearity properties, combined with the simplicity of analyzing the network structure, support the use of such SPNs as the basis for secure block ciphers.

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